Current Status and Future Developments in Understanding the Synthesis and Reactions of Heavy Nuclei

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Cold and Hot Fusion

- Cold Fusion
- Pb or Bi Target
- Heavier Projectile (Ca-Kr)
- E* ~ 13 MeV ((X,n) reaction, high survival)
- Significant fusion hindrance

- Hot (Warm) Fusion
- Actinide Target
- Lighter Projectiles (O-Ca)
- E* ~ 30 – 60 MeV (low survival)
- Small fusion hindrance

Overview of Our Understanding of the Synthesis of Heavy Nuclei

$$\sigma_{EVR} = \sigma_{CN} W_{sur}$$

$$\sigma_{CN} = \sum_{J=0}^{J_{\max}} \sigma_{capture}(E_{cm}, J) P_{CN}(E_{cm}, J)$$

$$\sigma_{capture} = \pi \lambdabar^2 (2J+1) T(E_{cm}, J) \qquad \pi \lambdabar^2 \ell_{\text{lim}}^2$$

Thus the problem becomes one of determining $P_{CN}W_{sur}$

Semi-empirical treatment of P_{CN}

Armbruster suggested (1985)

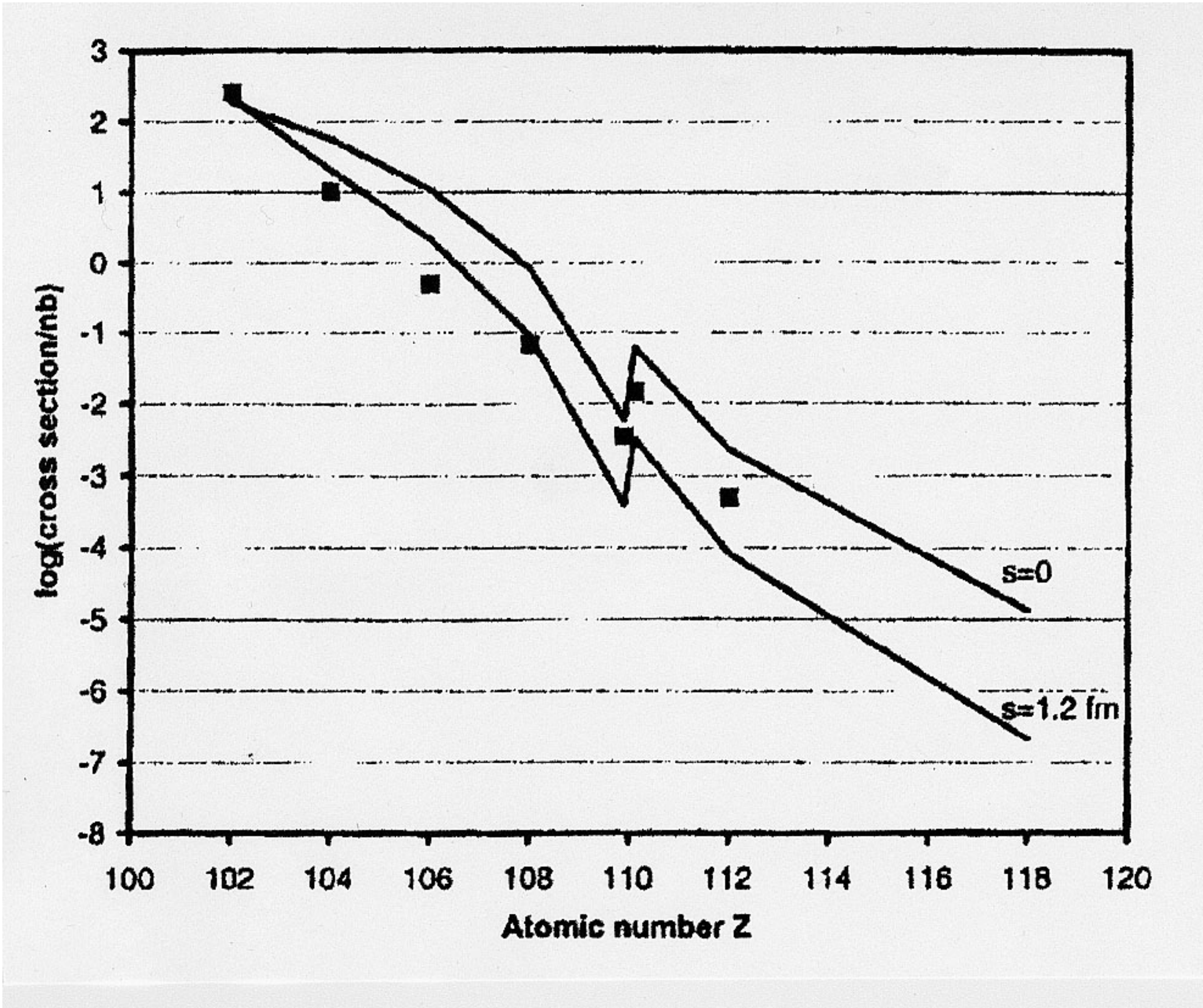
$$P_{CN}(E_{cm}, J) = 0.5[\exp(c(x_{eff} - x_{thr}))]$$

where the coefficient c has the value of 106 and the constant x_{thr} is 0.72 for actinide-based reactions and 0.81 for reactions involving Pb or Bi targets.

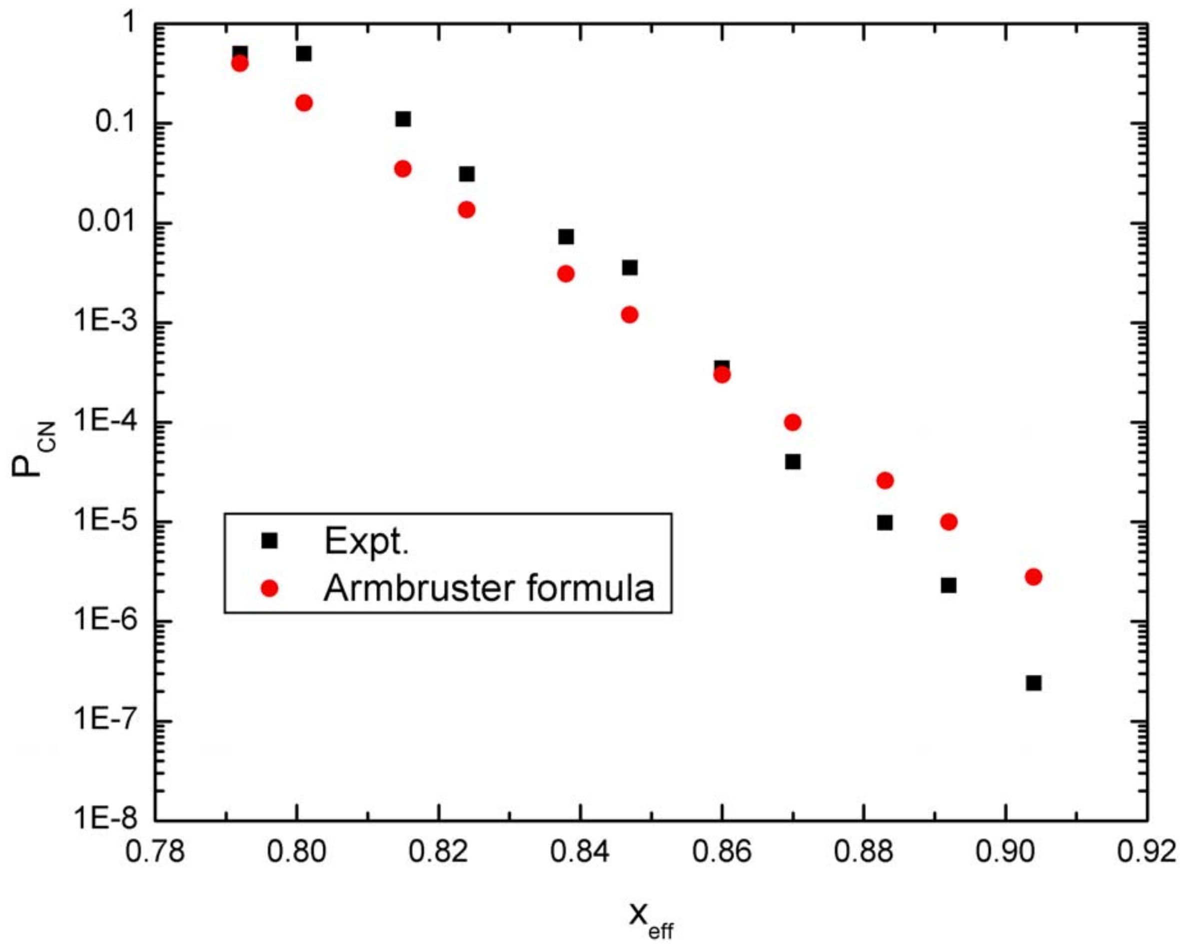
Swiatecki, et al, (2003) have suggested a similar form

$$P_{CN} \sim \exp(-B/T)$$

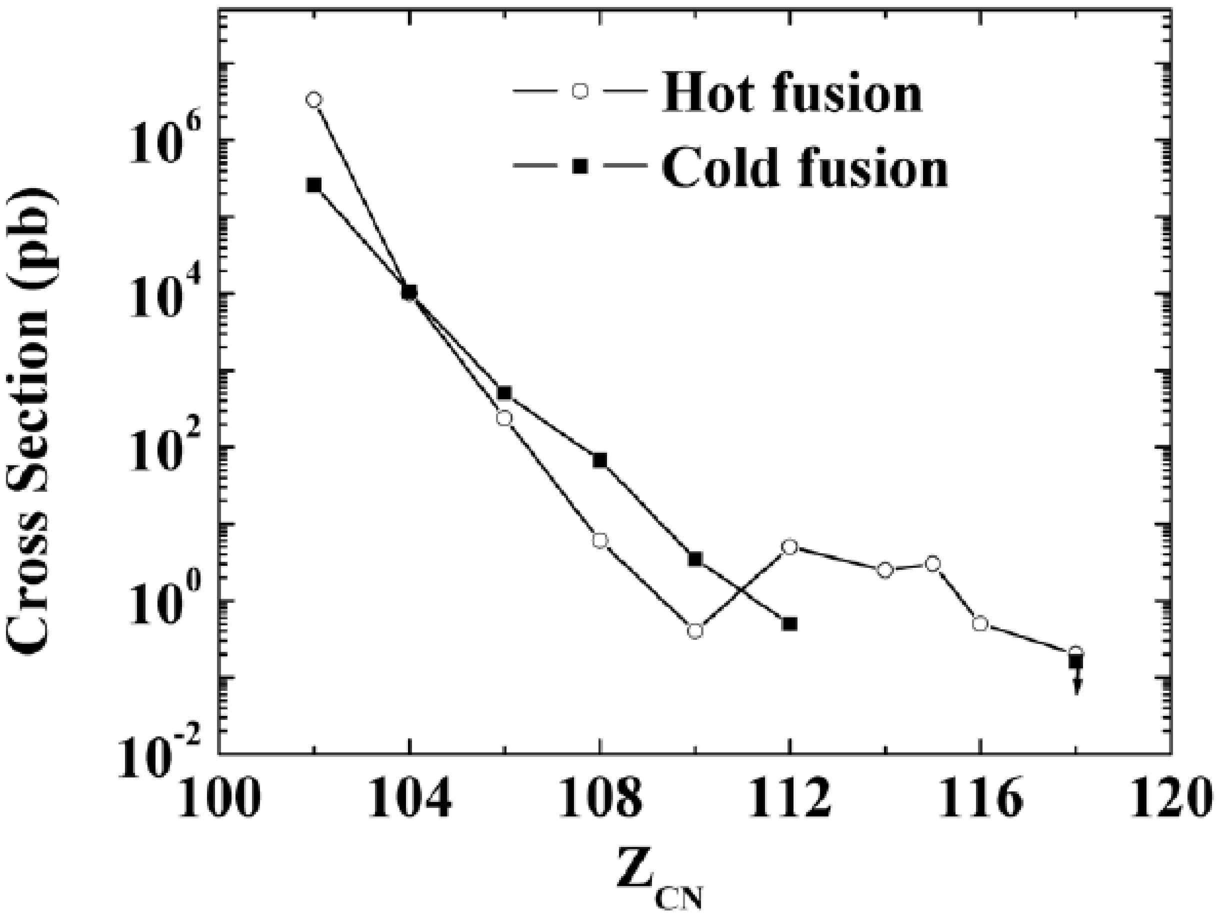
How well does this work?



How well does this work?



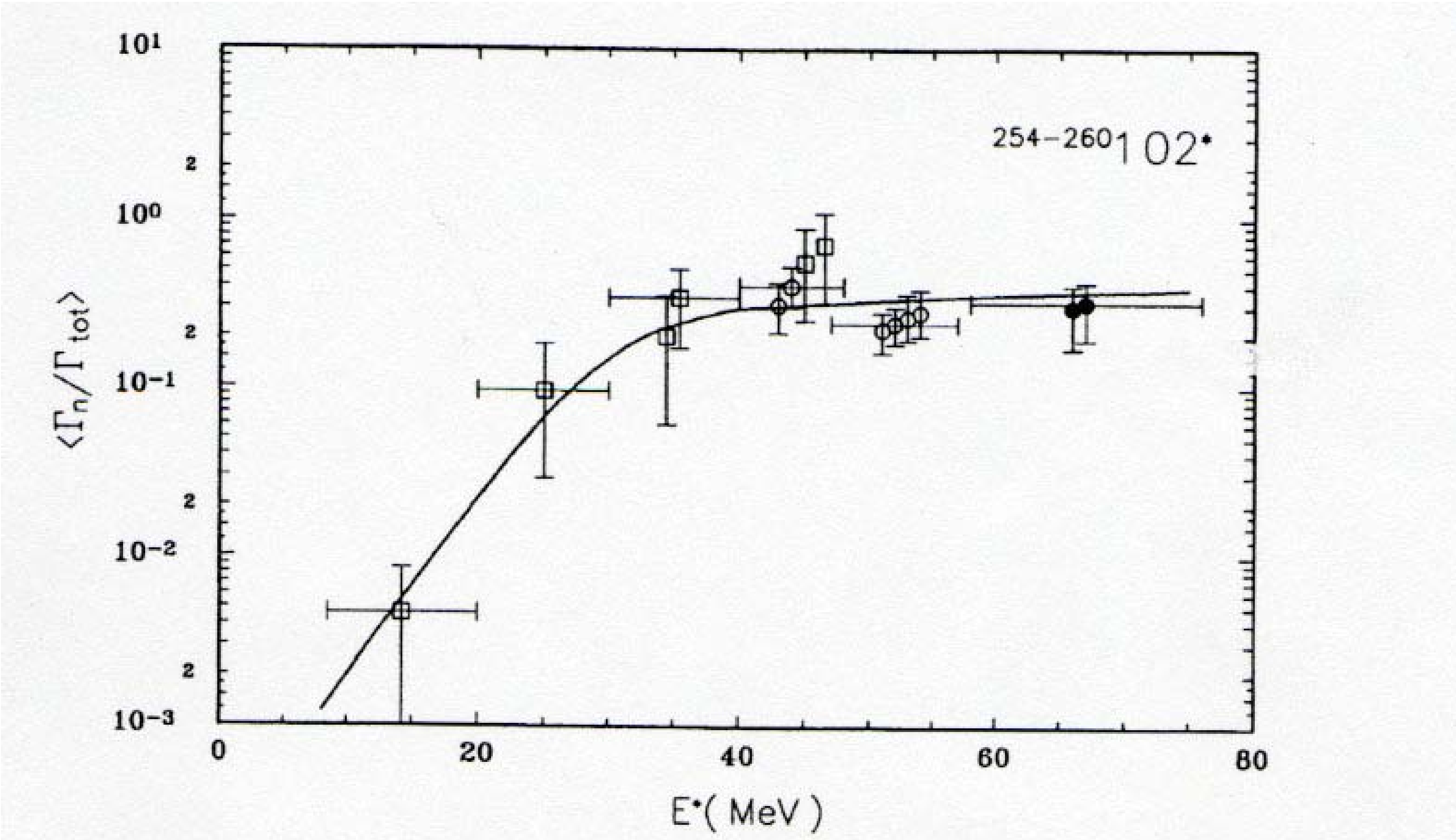
Hot Fusion



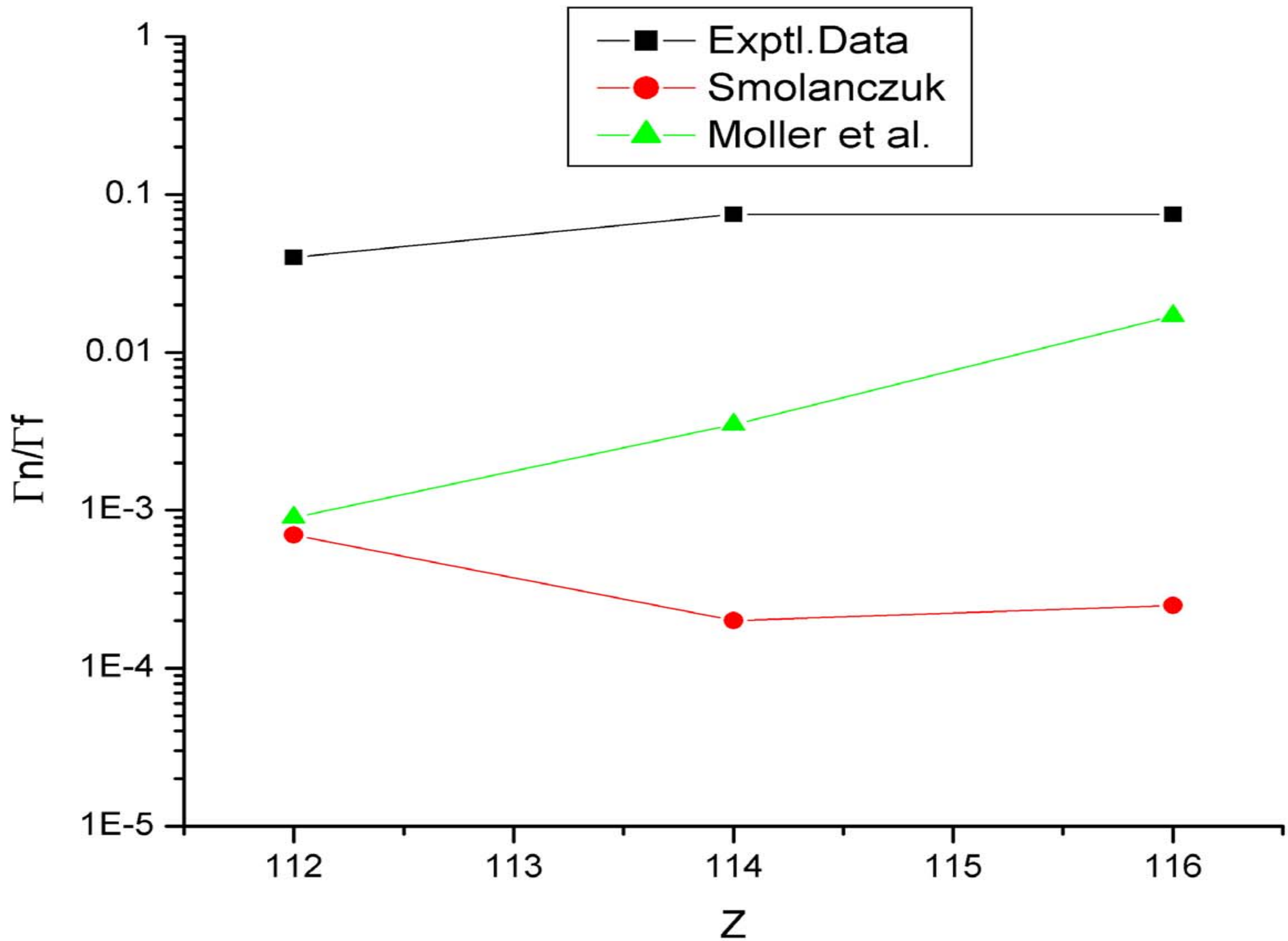
Hot fusion
Cold fusion
Cross Section (pb)
10^6
10^4
10^2
10^0
10^{-2}
100
104
108
112
116
120
Z_{CN}

The challenge is W_{sur}

Why Hot Fusion Works



Andreyev A N *et al* 1994 *Heavy-Ion Fusion: Exploring the Variety of Nuclear Properties* (Singapore: World Scientific) p 260



Exptl.Data
Smolanczuk
Moller et al.
1
0.1
0.01
1E-3
1E-4
1E-5
Γn/Γf
112
113
114
115
116
Z

Cross Bombardments

$$148\text{ MeV } {}^{26}Mg + {}^{232}Th \rightarrow {}^{258}No \rightarrow {}^{257}No \rightarrow {}^{256}No \rightarrow {}^{255}No \rightarrow {}^{254}No \rightarrow {}^{253}No \rightarrow {}^{252}No$$

$E^* = 61 \quad 51 \quad 42 \quad 33 \quad 24 \quad 14 \quad 6$

$$132\text{ MeV } {}^{25}Mg + {}^{232}Th \rightarrow {}^{257}No \rightarrow {}^{256}No \rightarrow {}^{255}No \rightarrow {}^{254}No \rightarrow {}^{253}No \rightarrow {}^{252}No$$

$E^* = 51 \quad 42 \quad 33 \quad 24 \quad 14 \quad 6$

$$120\text{ MeV } {}^{24}Mg + {}^{232}Th \rightarrow {}^{256}No \rightarrow {}^{255}No \rightarrow {}^{254}No \rightarrow {}^{253}No \rightarrow {}^{252}No$$

$E^* = 42 \quad 33 \quad 24 \quad 14 \quad 6$

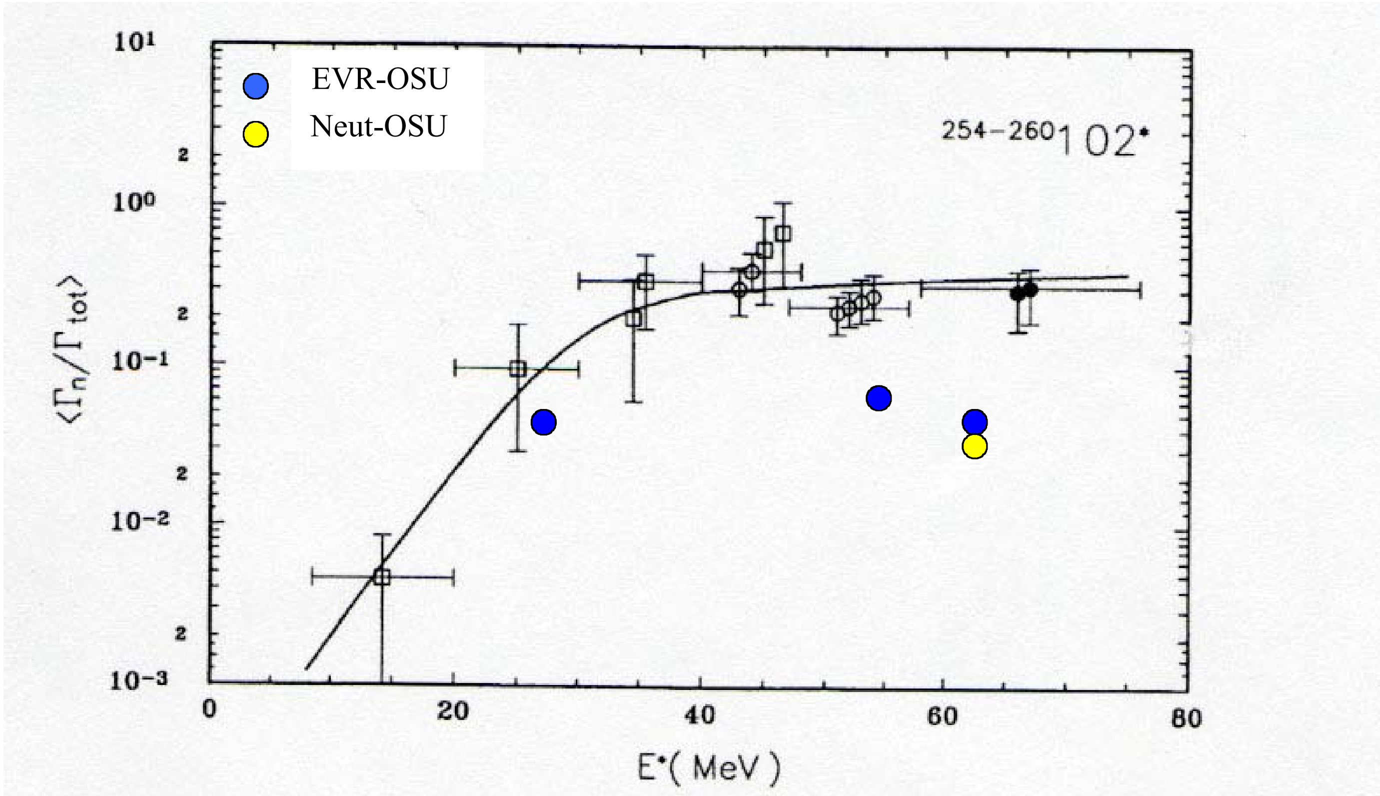


Figure 3. Recent measurements of Γ_n/Γ_f for excited No nuclei [8].

A Complementary Approach
Direct Neutron Counting

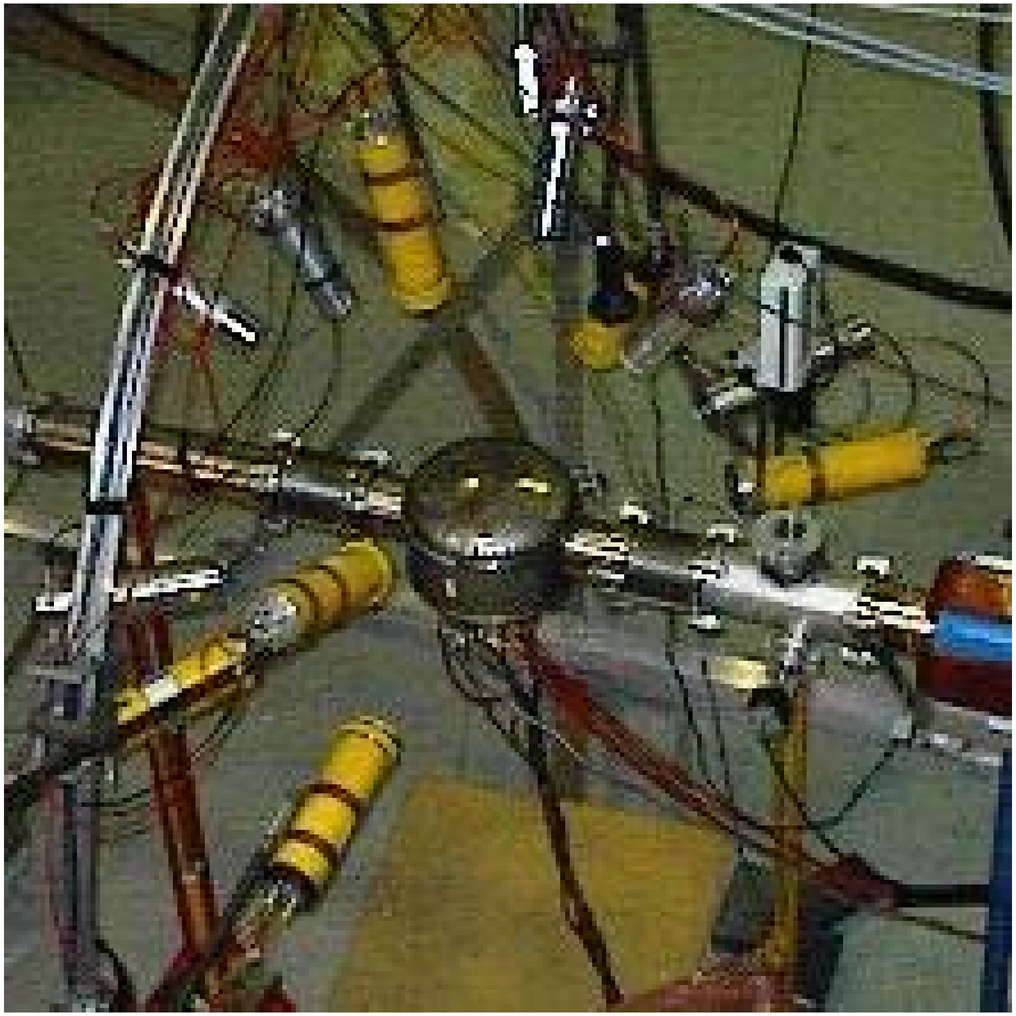
The Harding – Farley Experiment

We measured the angular correlation and energy spectra of the emitted neutrons relative to the beam axis and the direction of motion of the fission fragments.

These distributions are decomposed in a model-dependent, iterative manner into five components:

- **the pre-equilibrium neutrons emitted by the reacting nuclei prior to the establishment of statistical equilibrium**
- **the quasi-fission neutrons**
- **the neutrons emitted by the equilibrated compound nucleus prior to fission**
- **the neutrons emitted during the fission process, “the scission neutrons”**
- **the post-fission neutrons emitted by the accelerated fission fragments**

Apparatus



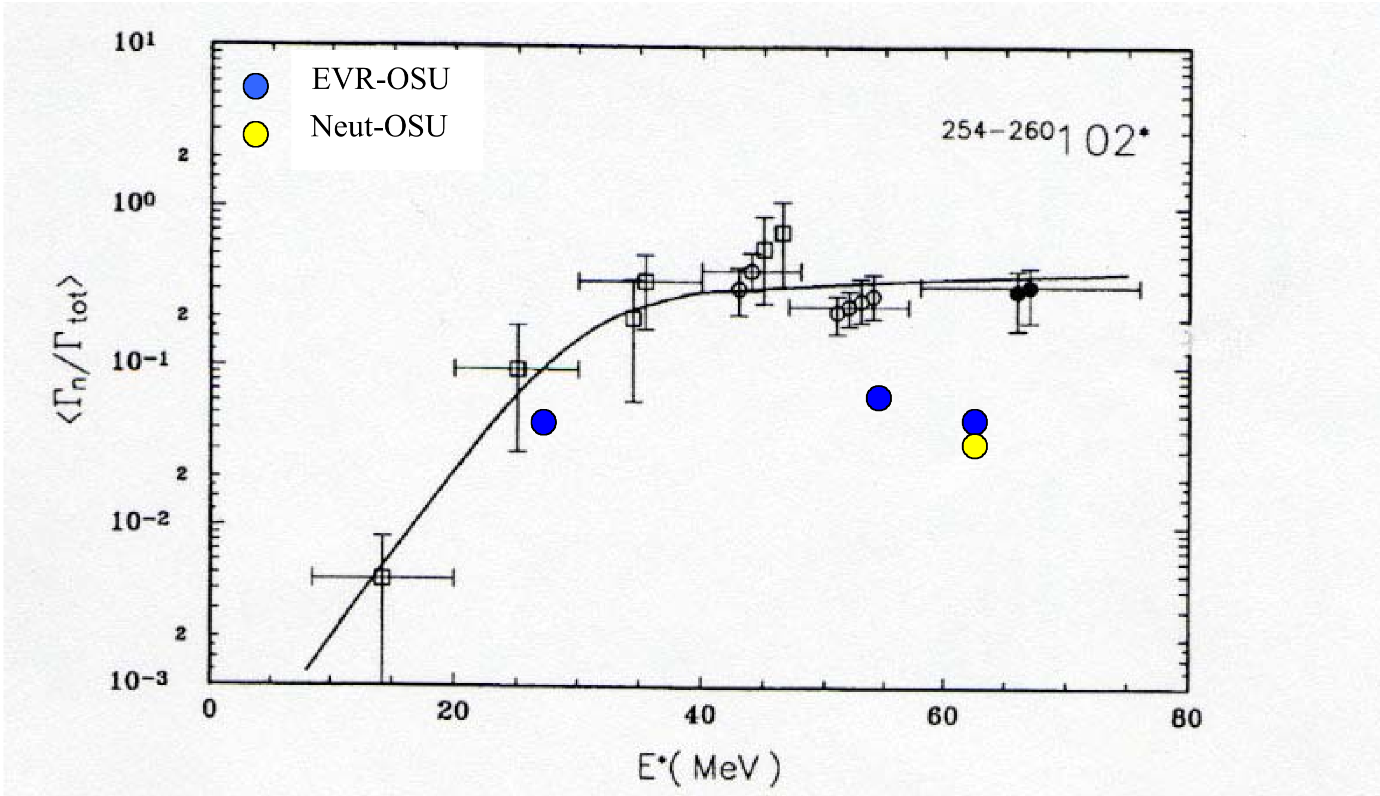


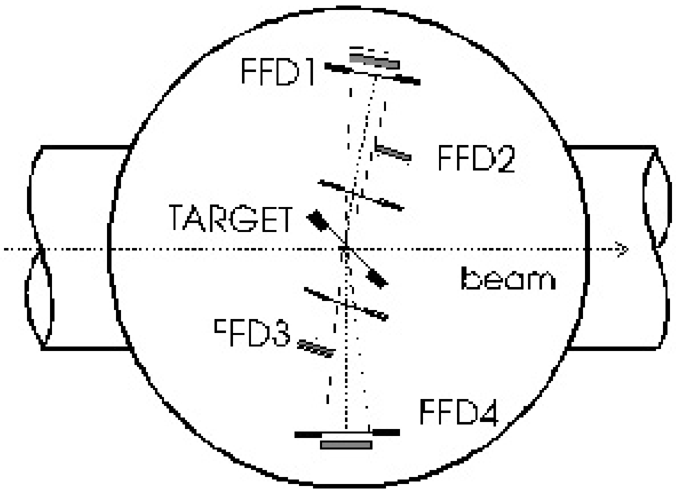
Figure 3. Recent measurements of Γ_n/Γ_f for excited No nuclei [8].

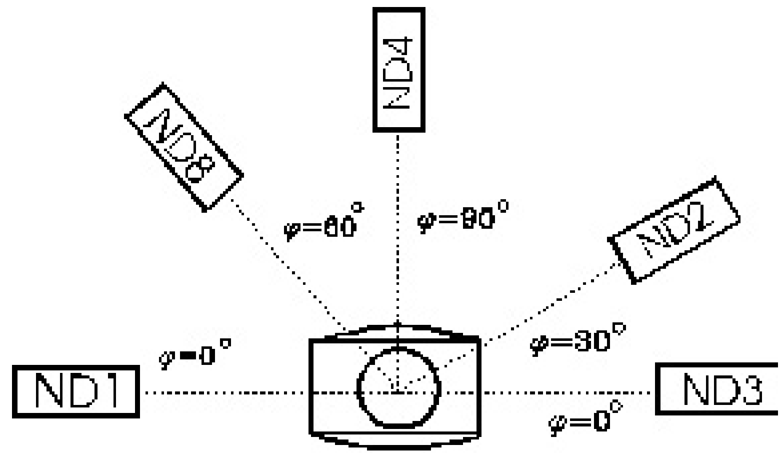
Applications of Neutron Multiplicity Measurements

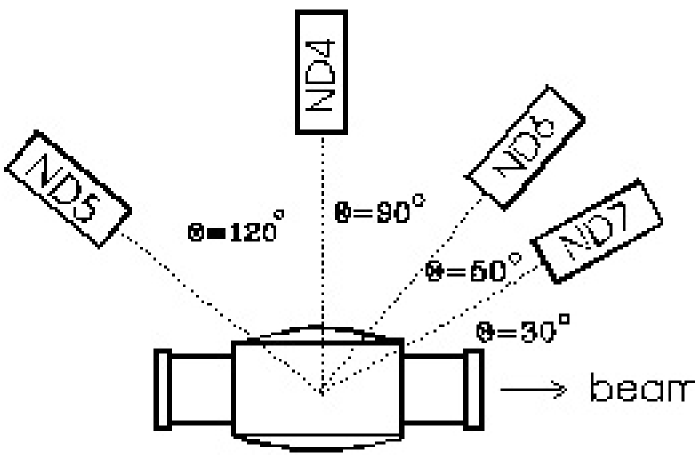
Accelerator Transmutation of Waste

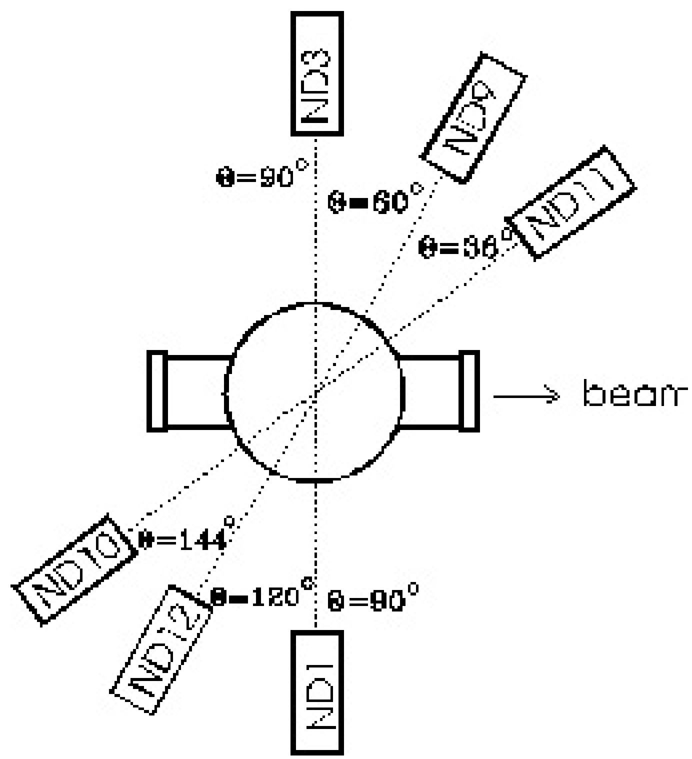
- 50 + 96 MeV p + ^{232}Th, ^{235,238}U and ^{237}Np.
- 12 stilbene neutron detectors, neutron energies deduced by TOF measurements.
- FF detected by TOF telescopes.

Experimental Setup

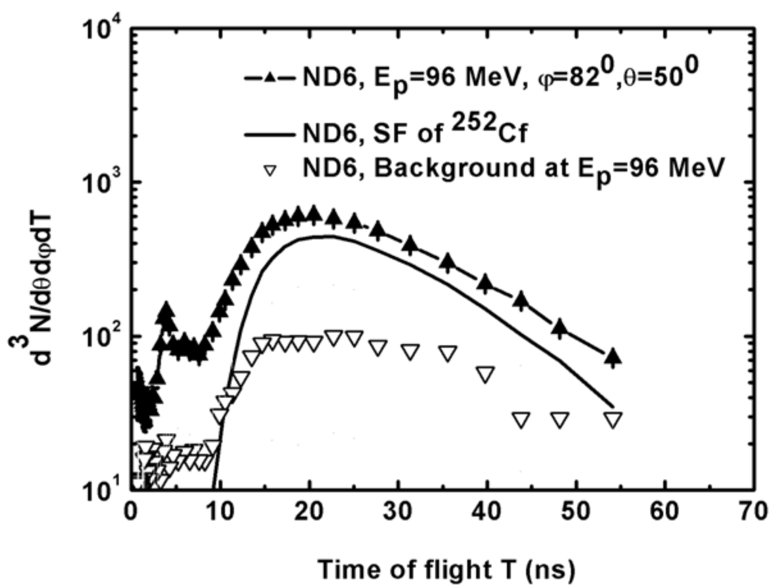


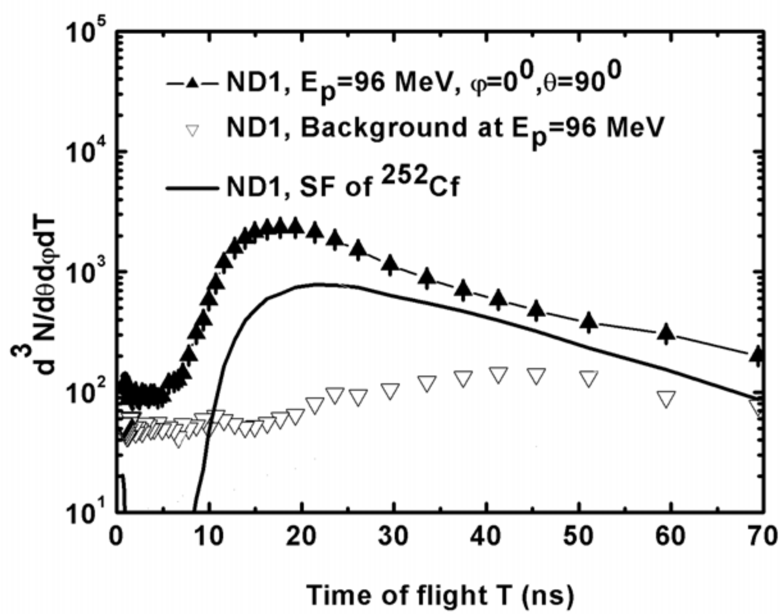






Representative TOF spectra

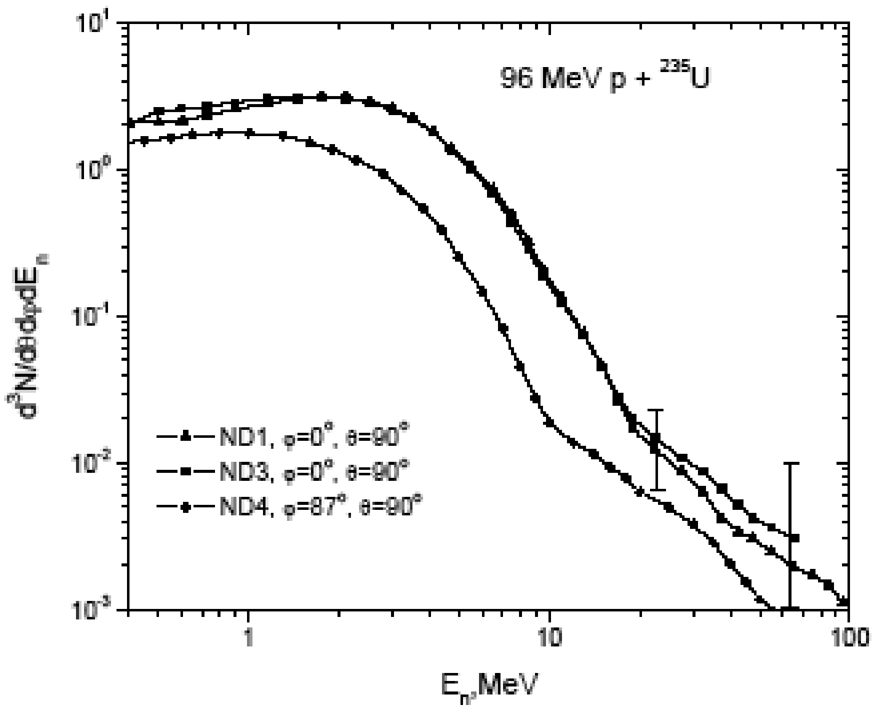




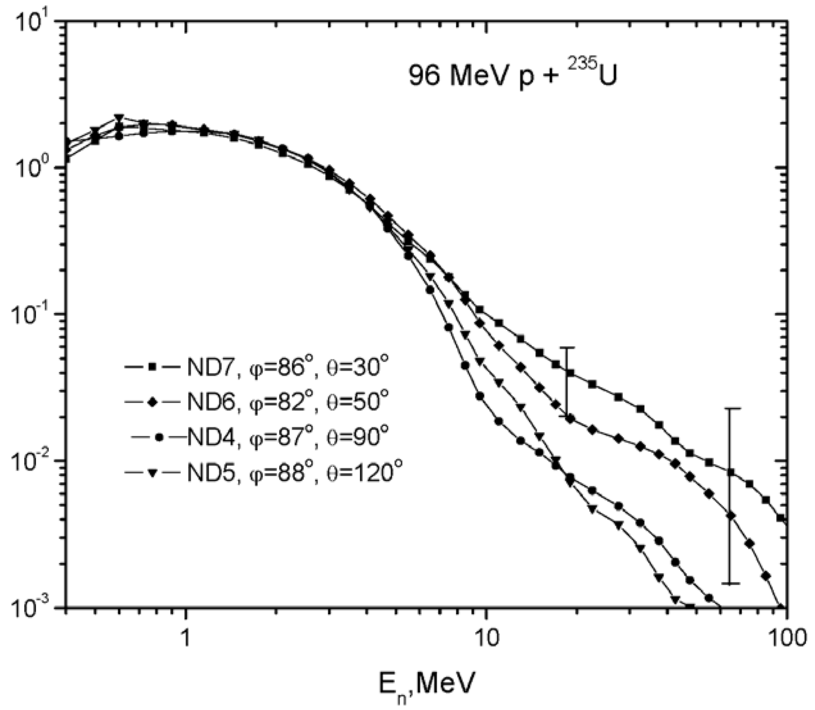
Perpendicular to fragment direction

Along fragment direction

Representative Energy Spectra



"fragment-related"

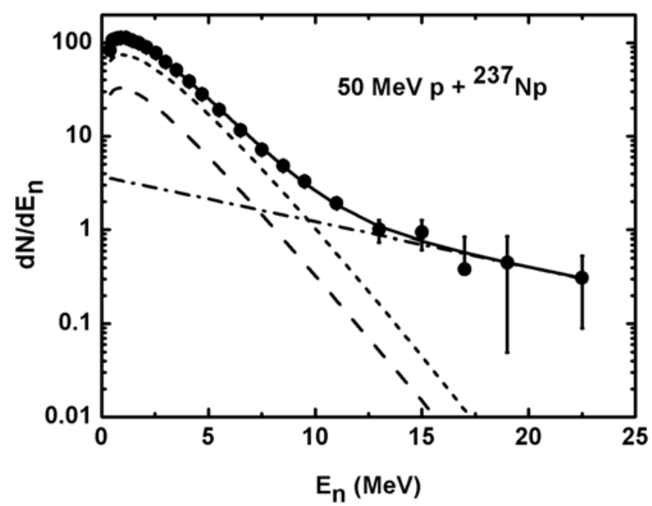


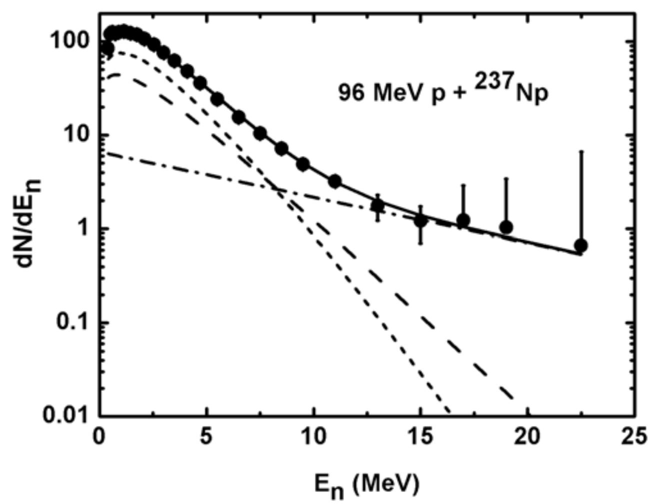
"beam-related"

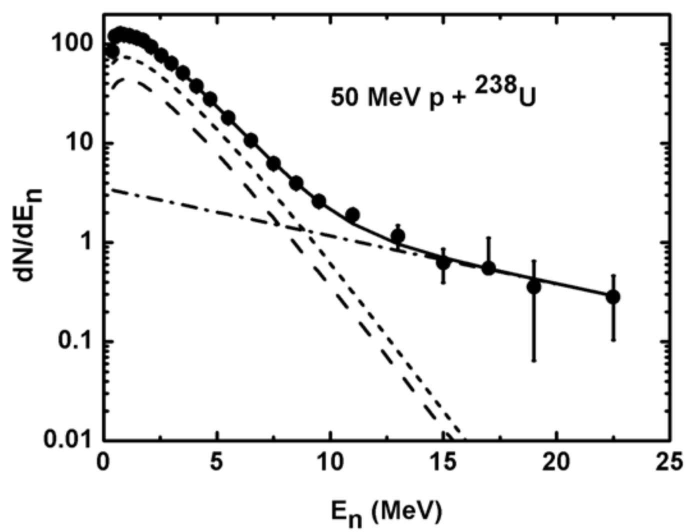
Decomposition of Spectra

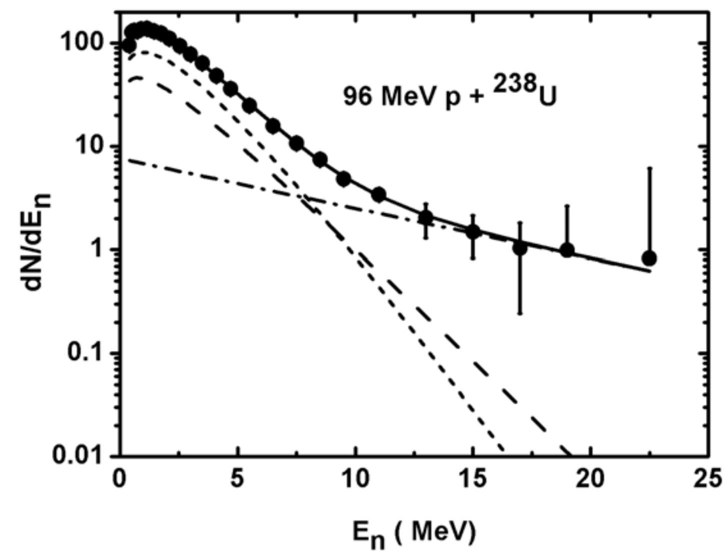
- Remove the pre-equilibrium component by fitting tail of neutron distribution above 15 MeV
- Assume all neuts at 0 degrees with respect to fragment are post-fission
- Assume all neuts at 90 degrees with respect to fragment are pre-fission
- Iterate

Results


50 MeV p + ^{237}Np
dN/dE$_n$
E$_n$ (MeV)
100
10
1
0.1
0.01
0
5
10
15
20
25


96 MeV p + ^{237}Np
dN/dE$_n$
E$_n$ (MeV)
100
10
1
0.1
0.01
0
5
10
15
20
25


50 MeV p + ^{238}U
dN/dE$_n$
E$_n$ (MeV)
100
10
1
0.1
0.01
0
5
10
15
20
25


96 MeV p + ^{238}U
dN/dE$_n$
E$_n$ (MeV)
100
10
1
0.1
0.01
0
5
10
15
20
25

Summary of ATW Work

- Pre-equilibrium neutrons are described adequately by Cascade-Exciton Model
- Equilibrium neutrons described by standard statistical model.
- No evidence for “fission delay” in these systems

Stockpile Science

(Project Start 7/03)

Proposed Measurements

- Average number of prompt neutrons ν and its dependence of fragment mass and energy (the “post-fission” neutrons)
- Energy spectra of these neutrons N(E,A)
- Energy spectra and multiplicities of pre-fission neutrons
- Energy spectra and multiplicities of any “scission” neutrons

for the energetic fission of

^{238}U, ^{237}Np, ^{238}Pu, ^{241}Am, ^{247}Bk, ^{244}Cm

Why?

Significant gaps in our knowledge of neutron emission in neutron-induced fission of these nuclides

- ν_{total} known for thermal fission of these nuclei (^{247}Bk ??)
- For ^{238}U and ^{237}Np, know $\nu_{prompt}(E^*)$ up to 10-20 MeV, limited data for ^{241}Am(n,f)
- Rest is *terra incognita*

Experimental Technique

- Use "surrogate reaction" d,pf to mimic n,f
- Do Harding-Farley measurement

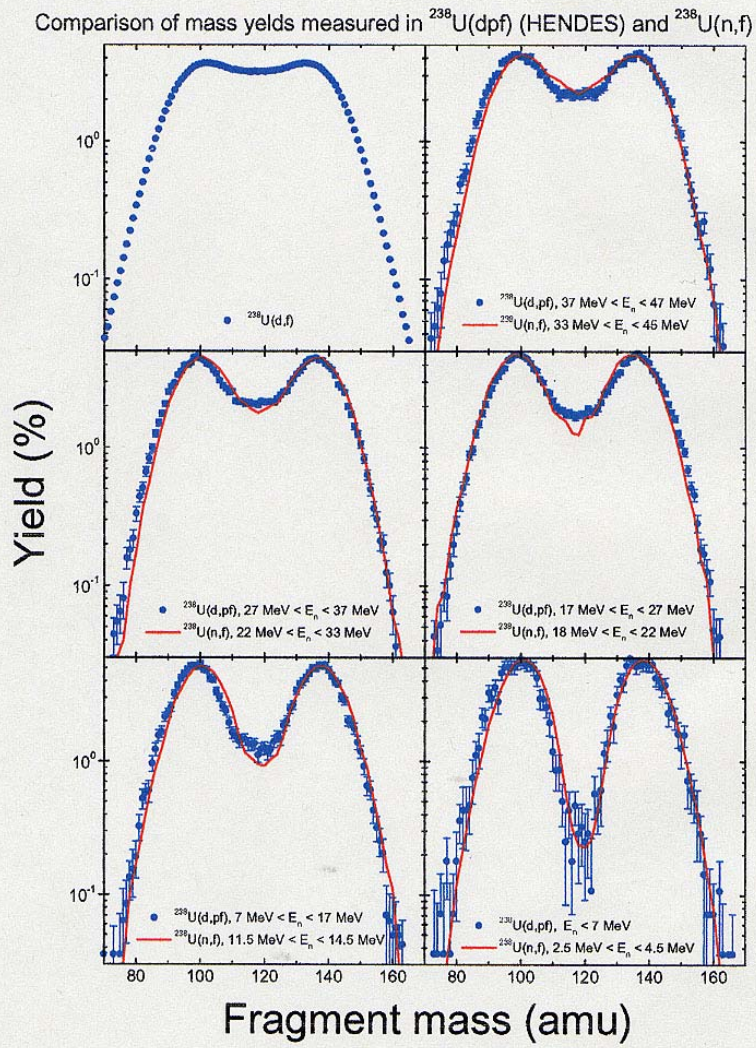
Is (d,pf) ≈ (n,f)?

Relevant data may be that of Jyvaskyla group (Yad Fiz **65**, 729 (2002); St. Andrews conference proceedings)

(d,pf), (n,f) J

- Mass distributions
- Cross Sections
- Post-fission neutrons

Fragment mass distributions were extracted for different proton energy bins and compared with the neutron induced fission of ^{238}U measured in Los-Alamos.



Dots with error bars - our data: d + ^{238}U, E_d = 65 MeV

Line - C.M.Zoller, PhD thesis, D17, THD, Darmstadt, 1995

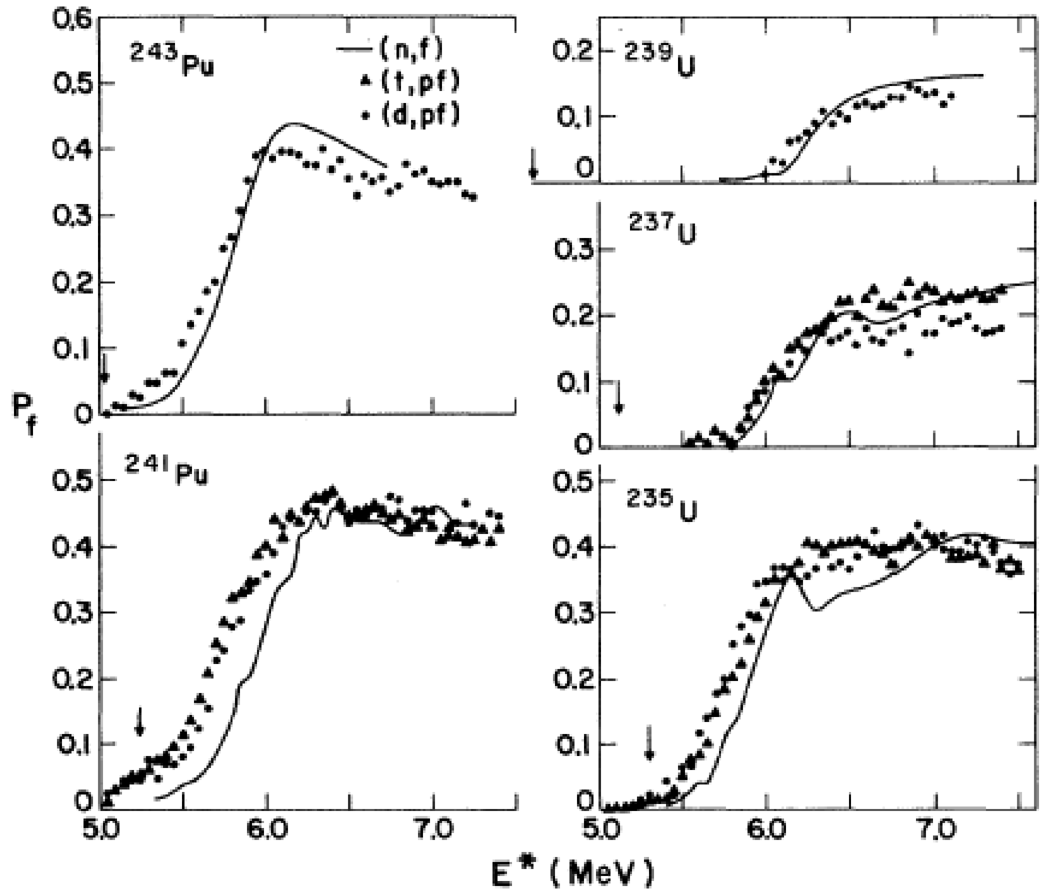
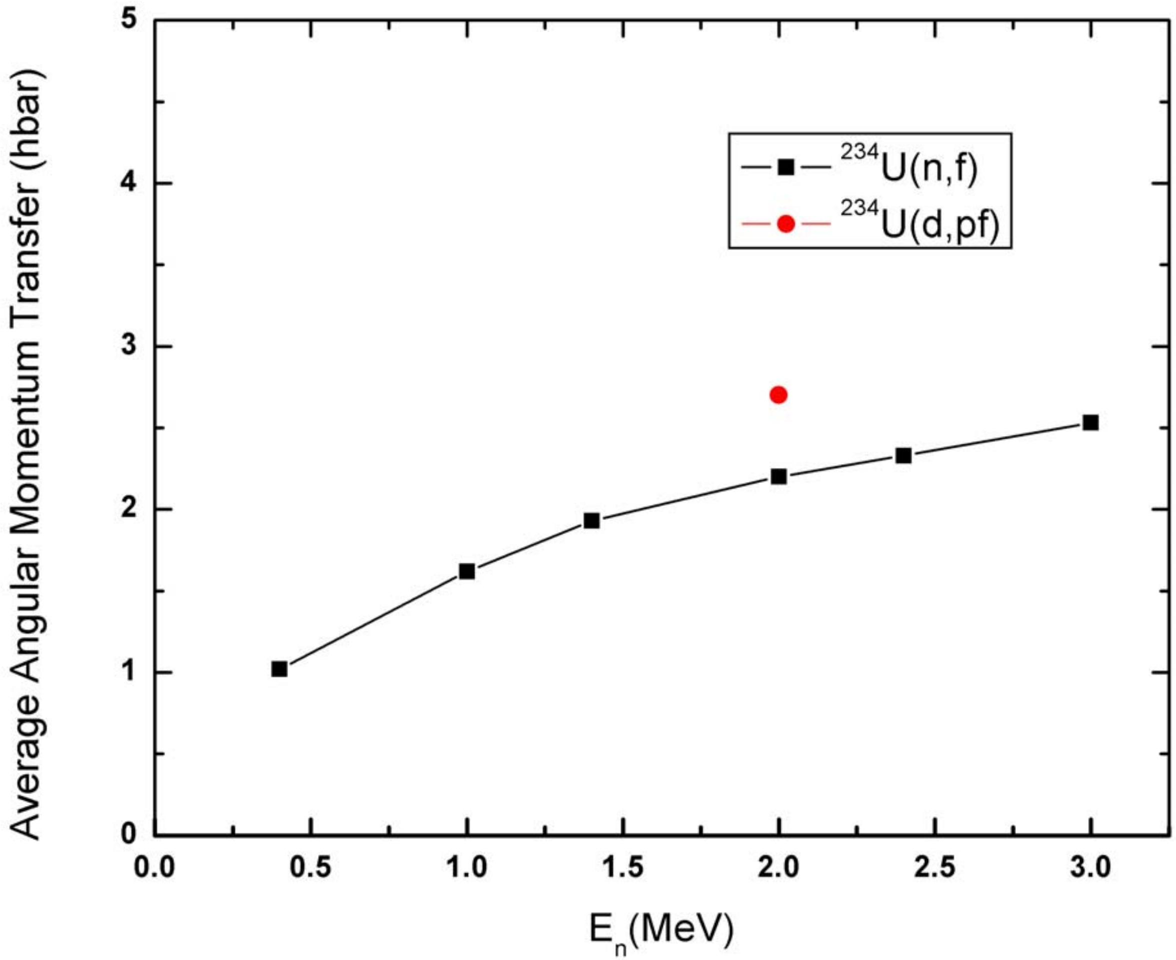


FIG. 9. Fission probabilities for the various reactions studied compared with results for (n,f) measurements. The (d,pf) results have been corrected for the effects of deuteron breakup reactions as described in the text. Arrows indicate the binding energy of the last neutron.

Typical Spin Distributions



Effect on Post-Fission Neuts

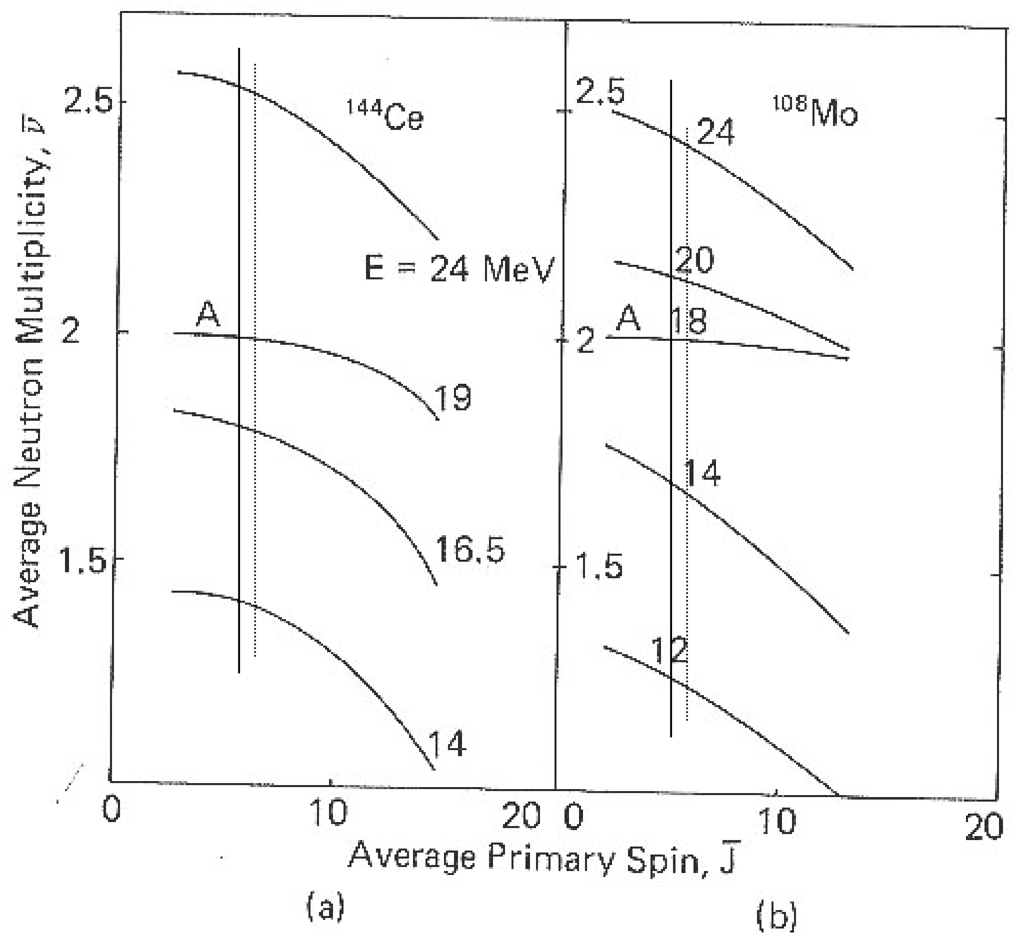


Fig. 8. Average neutron multiplicity $\bar{\nu}$ as a function of the average primary spin $\bar{J}$ and at different excitation energies E_x in (a) ^{144}Ce and in (b) ^{108}Mo.

Progress to date (since 7/03)

Modification of apparatus to optimize studies of (d,pf) reactions (stripping to continuum)

- Replacement of stilbene detectors by larger volume BC501A liquid scintillation detectors (4x eff)
- Substitution of a multiplane neutron detector geometry with an in-plane geometry.
- Mcp fragment detectors being replace by large area strip detectors (30-40x eff)
- Hemispherical thin-walled chamber to replace stainless steel cylindrical chamber
- Replace Windows/C-based DAQ system with a more robust system (in progress)

Progress (cont.)

- Fabrication of ^{238}U, ^{241}Am targets (by vacuum volatilization and molecular plating, respectively)
- ^{252}Cf calibrations of new apparatus
- Training/staffing the program with three new US students (Evenson, Brookhyser and Sprunger) along with two non-US students (Huang, Raik)